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A new technique to pyrolyse biomass in a microwave system: Effect of stirrer speed

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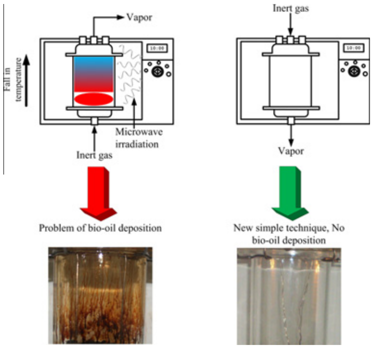
HIGHLIGHTS

- ▶ New MW pyrolysis technique helped to solve the problem of bio-oil deposition.
- ▶ The quality of bio-oil was improved with this method.
- ▶ Temperature, product yield and quality are affected by stirrer speed.
- ▶ MW absorber also played a role in the pyrolysis process.
- ▶ High phenolic bio-oil was obtained in this study.

GRAPHICAL ABSTRACT


Vapor
Fall in temperature
Microwave irradiation
Inert gas
Inert gas
Vapor
Problem of bio-oil deposition
New simple technique, No bio-oil deposition

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ABSTRACT

A new technique to pyrolyse biomass in microwave (MW) system is presented in this paper to solve the problem of bio-oil deposition. Pyrolysis of oil palm shell (OPS) biomass was conducted in 800 W and 2.45 GHz frequency MW system using an activated carbon as a MW absorber. The temperature profile, product yield and the properties of the products were found to depend on the stirrer speed and MW absorber percentage. The highest bio-oil yield of 28 wt.% was obtained at 25% MW absorber and 50 rpm stirrer speed. Bio-char showed highest calorific value of the 29.5 MJ/kg at 50% MW absorber and 100 rpm stirrer speed. Bio-oil from this study was rich in phenol with highest detected as 85 area% from the GC–MS results. Thus, OPS bio-oil can become potential alternative to petroleum-based chemicals in various phenolic based applications.

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1. Introduction

Oil palm shell (OPS) is one of the most abundant biomass available in Malaysia with an annual estimation of about 3 million tonnes (Abnisa et al., 2011). Moreover, it contains high lignin (45–48 wt.%) compared to other biomass (Kim et al., 2010). This lignin rich OPS biomass could be a good source of renewable phenol and phenolic chemical compounds (Effendi et al., 2008). If this biomass is underutilised, both energy and value added products cannot be produced. Thus, pyrolysis is one of the effective ways to convert this biomass into bio-fuels or value added products (Bridgwater, 2012).

Typically, in pyrolysis, biomass is thermally degraded under an inert environment resulting in liquid, solid and gaseous products depending on process condition. Conventional pyrolysis technology suffers from high energy consumption in form of electricity and poor product quality due to undesired secondary cracking reactions during pyrolysis process. During past decade, microwave (MW) pyrolysis has gained a wide acceptance in thermo-chemical community since it offers many advantages over other heating methods (Appleton et al., 2005). In MW, the heat is produced within the material unlike the conventional heating which is based on conduction and convection. This provides major advantage to MW

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in terms of rapid and volumetric heating, utilisation of a large-sized feedstock, better product quality, and enhanced chemical reactivity (Fernandez et al., 2011).

Based on the dielectric properties, the materials are classified into conductor, insulator, absorber and mixed absorber of MW. Hence, not all materials are good MW absorbers and biomass is one of them. Thus, carbonaceous materials such as char, activated carbon, graphite, etc. are generally mixed with biomass to induce pyrolysis since they are good MW absorber (Menendez et al., 2010).

Various types of biomass materials were pyrolysed using MW irradiation as listed in Table 1. Classically, researcher used quartz glass reactor to pyrolyse the biomass under MW. Different techniques were used by which the bio-oil can be collected during MW pyrolysis as depicted in Fig. 1. In most of the cases (Table 1), the inert gas (nitrogen, helium or CO_2) was introduced either from the bottom or from the top of the reactor. However, the vapours were entrained from the top of the reactor. As seen in Scheme III of Fig. 1, the material is usually at high temperature compare to other region of the MW reactor. This causes deposition of bio-oil on the wall of the glass reactor and other equipments. The bio-oil yield gets affected due to leftover of heavy fraction of bio-oil in the reactor. The problem of bio-oil deposition during MW pyrolysis was raised in the literature by Zhao et al. (2012). They used hot air with the help of electric heating device to avoid any vapour condensation in the experimental apparatus. Nevertheless, their system consists of an extra operation unit which may take up the energy in form of electricity.

In contrast to this, the present study provides a simple technique to avoid bio-oil deposition in the experimental equipments which followed the Scheme I as shown in Fig. 1. This technique (Scheme I) showed some advantages. Firstly, there was no bio-oil deposition on the wall of the reactor due to continuous purging of inert gas from the top of the reactor and immediate exit of vapour from the bottom of the reactor. Secondly, the vapour was instantaneously condensed as soon as they were released from the biomass. The need of glass connector to link the reactor outlet and condenser can be avoided. Furthermore, time consuming process of cleaning the equipments particularly the reactor after each run can be circumvented. Importantly, there was no loss of bio-oil in the process. In the past, none have used this simple technique to pyrolyse biomass in a MW system.

Very recently, Salema and Ani (2012a) were the first to implement the stirrer in MW pyrolysis of biomass. But they did not take into consideration the effect of stirrer speed. Apparently, no data is available in the literature showing the effect of stirrer speed on the temperature profile, product yield and bio-oil quality under MW irradiation.

Based on this, the objective of this research work was to pyrolyse oil palm shell (OPS) biomass using new technique under

Table 1
Survey of MW systems used by various researchers to carry out biomass pyrolysis.

Biomass	MW experimental set-up	Remarks	Scheme from Fig. 1
Wood Miura et al. (2004)	Nitrogen was introduced from the top of the reactor and bio-oil was collected at the bottom	Aspirator was used to extract the vapours out of the MW chamber. Bio-oil remained on the interior wall of the reactor was washed down into a collection bottle or tank with methanol	I
Pine wood sawdust Chen et al. (2008)	The reactor and tube system was purged by nitrogen	No further details about the collection of bio-oil or injection of nitrogen was provided	–
Rice straw Huang et al. (2008)	Nitrogen was purged into the system	No further details were provided about introduction of nitrogen and exit of vapours	–
Coffee hulls Dominguez et al. (2007)	Helium was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Wheat straw Budarin et al. (2009)	The MW reactor was fitted with a vacuum module to remove the vapour	No further details were provided	–
Oil palm biomass Salema and Ani (2011), Salema and Ani (2012a,b)	Nitrogen gas was introduced from the bottom and vapour were purged from the top of the reactor	Problem of bio-oil deposition on the walls of the reactors and equipments	III
Oil palm empty fruit bunches Omar et al. (2010)	Nitrogen gas was introduced from the bottom and vapour were purged from the top of the reactor	Bio-oil was expected to condense on the reactor	III
Rice straw and sawdust Jun et al. (2010)	Nitrogen gas was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Distillers dried grains with soluble Lei et al. (2011)	Nitrogen gas was used as inert gas	No further details were provided about introduction of nitrogen and exit of vapours	-
Corn stalk bale Zhao et al. (2010)	Nitrogen gas was introduced from the bottom and vapour were purged from the top of the reactor	Electrical heating tube was used before the condenser to avoid deposition of bio-oil	III
Microalgae Du et al. (2011)	Nitrogen gas was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Waste engine oil Lam et al. (2012)	Nitrogen gas was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Wheat straw Zhao et al. (2012)	Nitrogen gas was used as inert gas	The circulation air heated by an electric heating device was used to prevent the condensation of liquid-phase products on the walls of the quartz reactor and pipelines	II
Rice husk and sugarcane Wang et al. (2012)	Nitrogen gas was used as inert gas	Nitrogen gas was introduced from the bottom and vapour were purged from the top of the reactor	III
Paper mill sludge Jiang and Ma (2011)	Carbon dioxide and nitrogen was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Microalgae Hu et al. (2012)	Nitrogen gas was used as inert gas	The inert gas was introduced from the top but the vapour was entrained from top also	II
Sewage sludge Tian et al. (2011)	Nitrogen gas was used as inert gas	The inert gas was introduced from the side of the MW chamber and the vapour was entrained from side also	IV

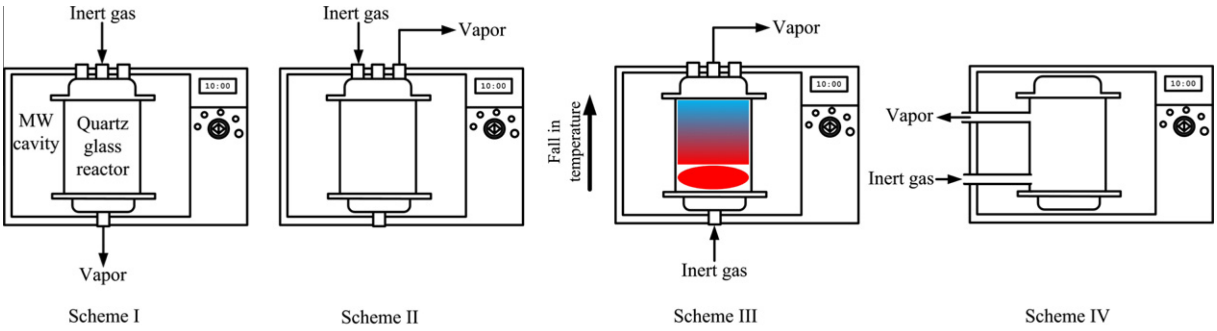

Fig. 1. Different pyrolysis technique under MW irradiation.

MW irradiation. In addition to this, the effect of stirrer speed on the MW pyrolysis of biomass was given particular attention. Results in regards of temperature profile, product yield and some characterization of bio-char and bio-oil were presented.

2. Methods

2.1. Materials

Oil palm shell (OPS) biomass used in this experiment was acquired from palm oil mill, located in Johor state of Malaysia. Oil palm shell was grinded to size of 1.4 mm. The inherent moisture content of the OPS was about 8.5 wt.%. Coconut based activated carbon of 3 mm particle size obtained from Laju Group of Companies, Malaysia was used as MW absorber. The particles of the MW absorber were bigger in size to shun any escape of carbon particles with vapours into bio-oil. Besides this, difference in biomass and MW absorber particle size facilitates for easy separation of MW absorber particles after pyrolysis experiments to reuse them back. Table 2 presents proximate and ultimate analysis of the OPS biomass on dry basis.

2.2. Experimental set-up

The schematic diagram shown in Fig. 2 represents the set-up for the MW assisted pyrolysis system. A modified domestic MW system with maximum power of 800 W and 2.45 GHz frequency was used to carry out the present research work. Quartz glass tube of 150 mm in length and 100 mm in diameter was used as reactor. This reactor was covered with three neck glass lid from the top and one neck glass lid from the bottom. The stirrer and inert gas were introduced from the central opening of three neck glass lid at the top while the other two was used for thermocouples. A thin wire mesh of 60 microns was used to support the biomass at the bottom of the reactor which also facilitated the exit of vapours from the bottom of the reactor into the condensing unit. An anchored two-bladed stainless steel stirrer with shaft diameter of 0.008 and 0.07 m wide blades was employed. The height of the stirrer was adjustable. The speed of the overhead stirrer was controlled via motor (90 W, 200–220 V) acquired from Tung electrical company Ltd. The stirrer speed fluctuated in the range of ±10 rpm due to MW field. But this took place in seconds because MW field in the cavity was based on duty cycle or ON/OFF mode. The two K-type thermocouples were connected to a Pico data acquisition system having an accuracy of ±1 °C and linked to a personal computer for continuous recording of real time temperature data. Thermocouple T1 is designated for bed surface temperature and T2 represents the bed inside temperature. MW leakages during the experiments were frequently monitored by MW leakage detector model TX90 acquired from Robin Professional Test Equipment, U.K as well as to ensure a safe working environment during the experiments.

Table 2
Chemical characteristics of OPS biomass on dry basis.

Proximate analysis (wt.%)		Ultimate analysis (wt.%)	
Moisture	8.5	C	55.35
Volatile	68.8	H	6.43
Fixed carbon	20.3	N	0.37
Ash	2.3	O	38.01

2.3. Methods

For each experiment, the percentage of the MW absorber was varied at 25 wt.% (25% carbon of the biomass weight), 50 wt.% (50% carbon of the biomass weight) and 75 wt.% (75% carbon of the biomass weight), and mixed with biomass before loading into the reactor., Nitrogen gas was supplied at the rate of 7 LPM (litres/minute) from the top of the reactor, to ensure an inert environment in the reactor before commencing the experiment. The nitrogen gas was continued throughout the experiment. Referring to previous study (Salema and Ani, 2012a), MW power of 450 W was kept constant and was enough to bring out pyrolysis process. The irradiation time of 30 min was also kept constant. However, stirrer speed was varied at 50, 100, and 150 rpm. The temperature of cooling water supplied to condensers was around 5–7 °C. After each experiment the weight of the bio-oil was determined, and the weight of bio-char was determined after the residues has cool down to room temperature. The yield of uncondensed gas was determined by difference. Duplication of experiments showed almost similar maximum temperature with some changes in temperature profiles. The yield of products showed difference of ±2 to 3 wt.%. However, the results in this study are the averaged values.

The chemical components present in the bio-oil were investigated by means of an Agilent Technologies 6890 GC using an HP-Ultra 2 capillary column (length 25 m, diameter 0.2 mm, film thickness of 0.33 μm). The GC initial oven temperature of 80 °C was raised to 200 °C at a rate of 10 °C/min, then to final temperature of 280 °C at a rate of 5 °C/min and was held constant for about 10 min at 280 °C. The injector temperature was monitored at 250 °C. Helium was used as the carrier gas. The above GC was connected to the inert Mass Selective Detector (MSD), Agilent Technologies 5975 series with scan as acquisition mode. The whole system was controlled by Chemstation software (Agilent) and the peaks were determined with help of Wiley library. The MSD acquisition parameters were: Electron ionisation (EI) mode, ion source temperature was 230 °C, emission current was 34.6 μA, ionization energy was 70 eV, and full scan range from 50 to 500.

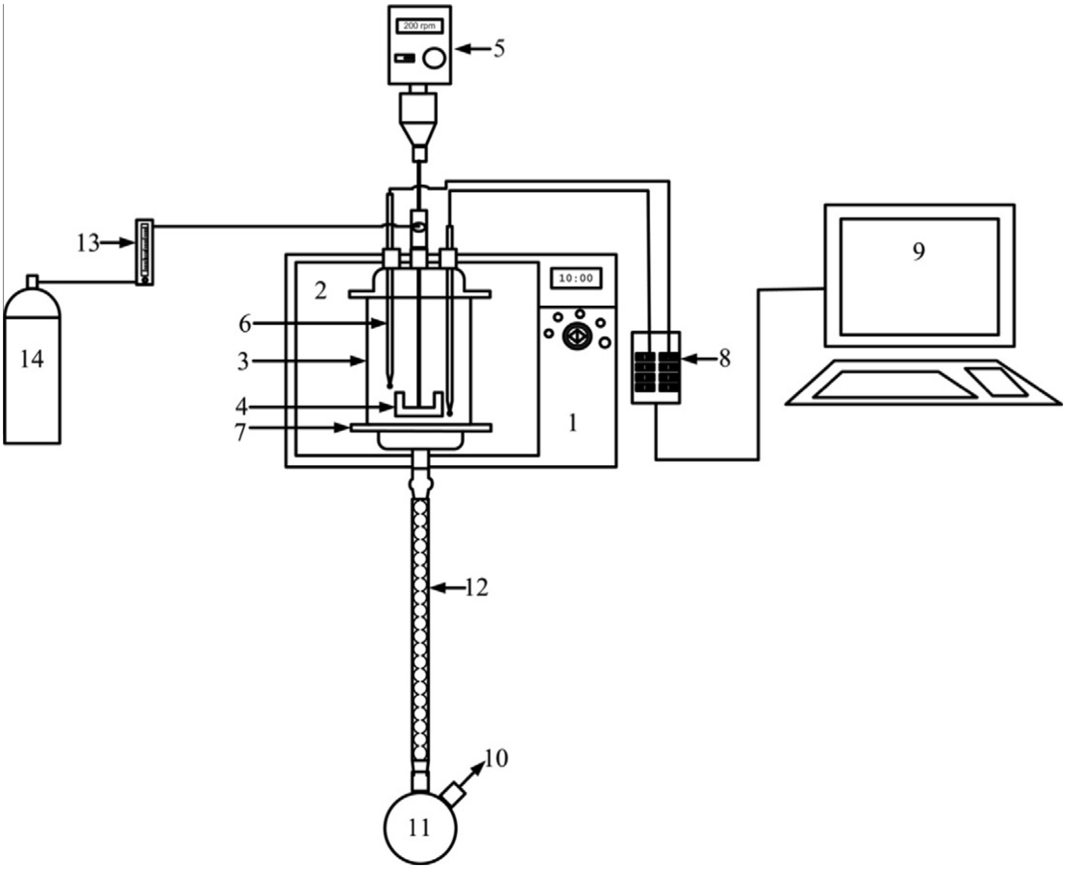

Fig. 2. Schematic diagram of MW pyrolysis system: (1) MW generator, (2) MW cavity, (3) Quartz glass reactor, (4) Stirrer, (5) Stirrer motor, (6) Thermocouples, (7) Wire mesh, (8) Temperature data acquisition system, (9) Personal computer, (10) Flue gas, (11) Bio-oil collector, (12) Condensing unit, (13) Rotameter, (14) Nitrogen gas.

The calorific value of the bio-char was determined by the use of an IKA C2000 bomb calorimeter. Analysis was run twice and the results were the averaged values.

3. Results and discussion

3.1. Outcome of new technique

Pyrolysis of OPS was successfully performed under MW irradiation without any bio-oil deposition on the reactor as well as the equipment wall. The problem of bio-oil deposition was solved by introducing inert gas from the top and exit of vapours from the bottom of the reactor. The incoming nitrogen gas from the top restricted any escape of the vapour from the top of the reactor. It was observed that the vapour could easily entrain from the bottom of the reactor. Since the condensers were directly attached to the bottom of the reactor as seen in Fig. 2, the vapours were rapidly condensed into bio-oil. Thus, the losses in bio-oil yield can be avoided due to this rapid condensation and elimination of bio-oil deposition from the reactor wall. Furthermore, cleaning of reactor and other equipments after the pyrolysis process was saved because of this new technique. There was no major problem observed in this study. This was proved by the temperature profiles and product yield as discussed in subsequent Sections.

3.2. Temperature profiles

The real time temperature profiles obtained at varying MW absorber (activated carbon) percentage is shown in Fig. 3 at 50 rpm stirrer speed. The sinusoidal nature of the temperature profiles were result of the cyclic on/off working nature of the magnetron (MW generator), commonly known as duty cycle. All domestic MW systems work in this mode and its detail could be found elsewhere (Salema and Ani, 2011). The temperatures tend to decrease as the MW absorber percentage was increased. This results were in agreement with previous work on MW pyrolysis (Salema and Ani, 2011, 2012a,b). The temperature might have dropped because of selective heating nature of MW irradiation at high MW absorber percentage (75%). In this, the MW absorber gets heated due to localised heating and the heat cannot be transferred efficiently to the biomass materials which delays the heating period. At low MW absorber percentage viz. 25%, the volatile matter are released much earlier from the biomass materials and thus, can attend high temperature. Thus, a very high temperature was observed in the study of Omar et al. (2010) with low MW absorber percentage (below 15%). Similarly, other researchers (Dominguez et al., 2007; Du et al., 2011) used about 20 wt.% MW absorber to achieve high temperature during biomass pyrolysis under MW irradiation.

Another interesting observation was the increase in the bed surface temperature (the red line in* Fig. 3) with increase in MW absorber percentage. The temperature gradient between bed inside and bed surface temperature could be decreased with the increase of MW absorber percentage. Nevertheless, MW heating can provide uniform temperature distribution within the material. From Fig. 3, it could be observed that after approximately 15 min the temperature profiles almost attained plateau except that for 75% MW absorber. After this time, the vapours were almost ceased which indicated completion of pyrolysis process.

The effect of stirrer speed on the maximum bed inside and bed surface temperature is depicted in Fig. 4. For bed surface (Fig. 4A)

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[*] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.

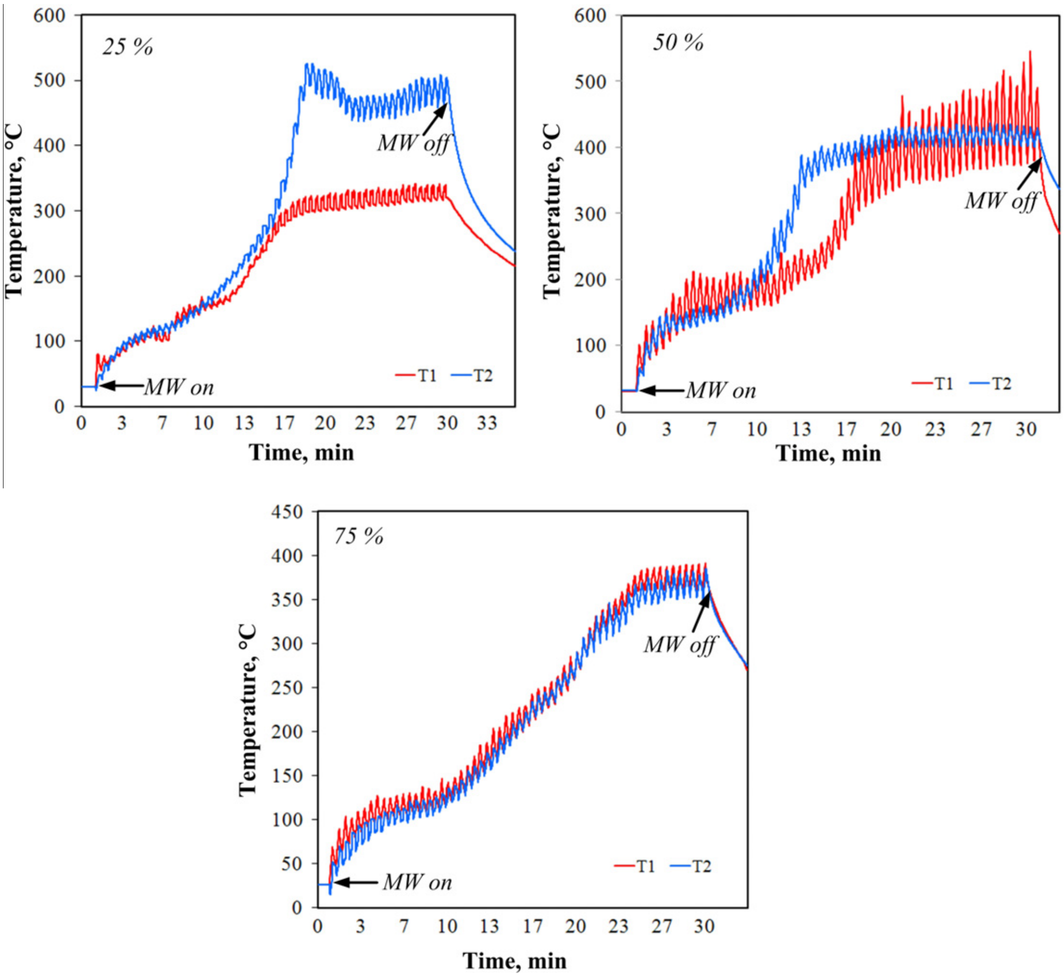

Fig. 3. Real time temperature profile of MW pyrolysis of OPS biomass at different MW absorber percentage but at constant stirrer speed (50 rpm).

there was increase in temperature after 100 rpm except for 50% MW absorber whereby temperature dropped from 50 to 150 rpm. However, in case of bed inside (Fig. 4B), the temperature increased till 100 rpm and than dropped for 50% and 75% MW absorber. But it increased almost linearly in case of 25% MW absorber. Overall, bed inside temperature was higher than surface temperature. The results on the effect of stirrer speed cannot be compared with other research work because there was no definite study regarding the effect of stirrer speed on the temperature profile found in the literature.

From Fig. 4, the desired pyrolysis temperature (450–550 °C) could be obtained using 25% MW absorber @ 50 rpm and 50% MW absorber @ 50 and 100 rpm. Usually, temperature higher than 550 °C will encourage secondary reactions and hence it could favour gaseous products (Luque et al., 2012). On the other hand, Salema and Ani, (2012a) reported desired pyrolysis temperature of 500 °C at 50% MW absorber and 200 rpm stirrer speed. It was difficult to conclude an optimum stirrer speed from the study. However, from our point of view 100 rpm could be considered as optimum value since below and above this speed, the temperature was observed to change. Since MW pyrolysis greatly depends on the physio-chemical properties of the biomass, the optimum value of stirrer speed cannot be generalised for other biomass. The investigation emphasised the role of stirring action on the MW pyrolysis process. According to Herrero et al. (2008), stirring or agitation of material in MW heating is essential to reduce temperature gradient. This is achieved due to enhance heating rate within the material due to continuous stirring.

3.3. Product yield

Bio-oil yield tend to decrease with increase in stirrer speed and MW absorber percentage as shown in Fig. 5a. The highest bio-oil yield of 28 wt.% was obtained at 25% MW absorber and 50 rpm, while the lowest bio-oil yield of 12 wt.% was found at 75% MW absorber with 150 rpm stirrer speed. The highest bio-oil yield at 25% MW absorber and 50 rpm could be due to favourable pyrolysis temperature of about 500 °C. Previous study obtained highest bio-oil yield (17 wt.%) at 50% MW absorber for OPS (Salema and Ani, 2012a) but at 200 rpm stirrer speed which was lower than present study. Thus, it could be deduced that low stirrer speed of 100 rpm and below up to 50 rpm is recommended in order to obtain high bio-oil yield.

Yield of other products such as char and gas is shown in Fig. 5b. The increase in gas yield at 50% and 75% MW absorber was suggested due to secondary reactions of the pyrolysis vapour. The gas and char yield varied in range of 38–47 wt.% and 28–41 wt.%, respectively. The secondary reactions taking place in the char at high MW absorber percentages (50% and 75%) might also produce non-condensable gaseous components which would also contribute to the increase in gas yield. The catalytic effect of activated carbon (MW abosrber) during MW pyrolysis cannot be ignored. Temperature could be another reason for fluctuation in product yields. It is evident from Fig. 4 that 75% MW absorber showed lowest temperature and thus bio-oil yield obtained at 75% MW absorber was also lowest with all stirrer speed (Fig. 5b). Previous researchers have stated that increase in temperature during

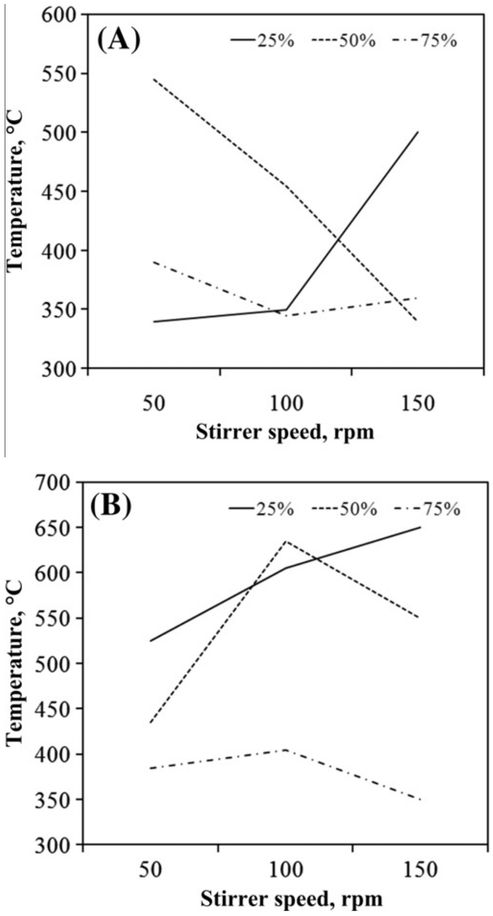

Fig. 4. Maximum bed (A) surface and (B) inside temperature during MW pyrolysis of OPS biomass in presence of MW absorber (25%, 50% and 75%).

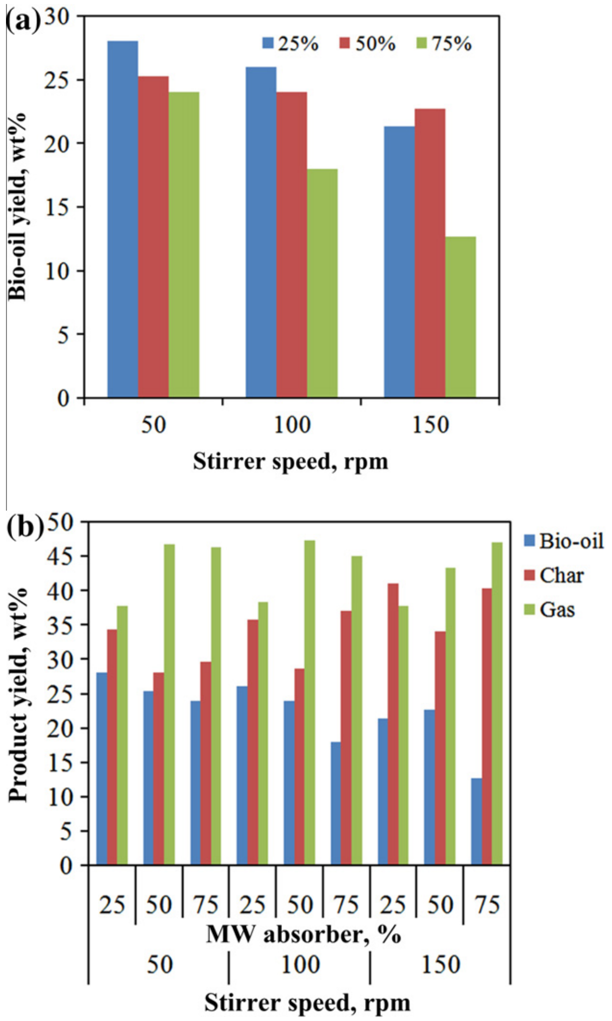

Fig. 5. Effect of stirrer speed and MW absorber percentage on (a) Bio-oil and (b) product yield from MW pyrolysis.

pyrolysis usually lead to formation of more gaseous product compared to liquid or bio-oil (Bu et al., 2011). In general, MW pyrolysis usually produces higher gas fraction compared to conventional heating (Menendez et al., 2010).

3.4. GC–MS characterisation of the bio-oil

The chemical analysis of typical OPS bio-oil is depicted in Tables 3 and 4. Surprisingly, the bio-oil from this study mainly consisted of phenol and its compounds. The results indicated that MW pyrolysis produced higher amount of phenol compared to conventional pyrolysis of OPS (Islam et al., 1999; Kim et al., 2010; Kawser and Ani, 2000). These results were in good agreement with other researchers (Bu et al., 2011; Lei et al., 2011; Ren et al., 2012). Thus, this type of bio-oil has great potential to become source of phenol in many phenolic applications which can substitute the petroleum based phenol. Nevertheless, compared to previous work, this study revealed highest amount of phenol (~85 area%) in OPS bio-oil at 100 rpm stirrer speed and 75% MW absorber (Table 4). Formation of phenolics in bio-oil is believed to be produced from decomposition of lignin. Lignin is considered to be composed of phenolic monomers and can become a good source of renewable phenolic resins (Effendi et al., 2008) by using pyrolysis process. Another benefit of this high value compound would be direct use of bio-oil in phenolic applications without undergoing extensive separation process thus making significant economic advantage for the industry.

From the Table 3, the effect of stirrer speed on the chemical compounds of bio-oil can be noticed. This bio-oil was taken from 25% MW absorber and subjected to GC–MS analysis. An optimum amount of phenol (45.5 area%) was detected at 100 rpm stirrer speed. With further increase in stirrer speed such as 150 rpm, the production of phenol and its compounds was not favoured. Other major chemical compounds identified were 2-methoxy-phenol, 2-methoxy-4-methyl-phenol, and 2,6-dimethoxy-phenol. The presence of chemical compounds such as *o*-cresol, *p*-cresol, 4-ethyl-2-methoxy-phenol, 2-methoxy-4-vinyl phenol, benzene and others depended on variation of stirrer speed. Formation of chemical compounds might be due to fluctuation in temperature associated with stirrer speed as shown in Fig. 4. The stirring action might influence the heating rate during MW pyrolysis which can lead to heterogeneous reactions. It has been reported that other pyrolysis operating conditions such as temperature, particle size, heating rate, vapour residence time, feed characteristics might influence the yield of phenol in the bio-oil (Amen-Chen et al., 2001). The phenol content was found to increase with rise in temperature for different biomass (Demirbas, 2007). This might happen due to continuous secondary degradation reactions with increase in temperature (Mohan et al., 2006). Furthermore, according to them, pyrolysis of lignin produces phenol due to ether and carbon–carbon linkage.

Table 4 present the chemical compounds found in OPS bio-oil for different MW absorber percentage but at constant stirrer speed of 100 rpm. The highest amount of phenol yield (~85 area%) was

Table 3
Chemical compounds in OPS bio-oil obtained from MW pyrolysis at different stirrer speed but for 50% MW absorber.

Chemical compounds	Peak area (%)		
	Stirrer	Speed	rpm
	50	100	150
Phenol	38.9	45.5	37.1
2-Methyl-phenol (*o*-cresol)	–	2.5	1.9
4-Methyl-phenol (*p*-cresol)	–	1.5	1.9
2-Methoxy-phenol (Guaiacol)	7.9	8.7	7.8
2-Methoxy-4-methyl-phenol	5.9	6.5	5.8
4-Ethyl-2-methoxy-phenol	–	6.7	6.2
2,6-Dimethoxy-phenol (Syringol)	8.9	9.8	8.4
2-Methoxy-4-vinyl phenol	1.3	–	1.0
2-Methoxy-4-(1-propenyl)-phenol	2.2	–	–
2,6-Methoxy-4-(2-propenyl)-phenol	2.0	–	1.4
Benzene	5.6	–	–
1,4-Benzendiol	–	–	1.5

(–) Not detected.

Table 4
Chemical compounds in OPS bio-oil obtained from MW pyrolysis at different MW absorber but for 100 rpm stirrer speed.

Chemical compounds	Peak area (%)		
	MW	Absorber	%
	25	50	75
Phenol	44.1	45.5	84.7
2-Methyl-phenol (*o*-cresol)	0.4	2.5	–
4-Methyl-phenol (*p*-cresol)	–	1.5	–
2-Methoxy-phenol	7.6	8.7	6.7
2-Methoxy-4-methyl-phenol	5.2	6.6	2.1
4-Ethyl-2-methoxy-phenol	–	6.7	–
2,6-Dimethoxy-phenol	8.7	9.8	–
2-Methoxy-4-vinyl phenol	1.7	–	–
2-Methoxy-4-(1-propenyl)-phenol	2.3	–	–
2,6-Methoxy-4-(2-propenyl)-phenol	2.4	–	–
Benzene	–	–	–
1,4-Benzendiol	–	–	–

(–) Not detected.

found at 75% MW absorber. The bed inside and surface temperature at 75% MW absorber and 100 rpm stirrer was about 405 and 345 °C, respectively. Thus, it can be deduced that for the present MW pyrolysis study, temperature in between 400 to 450 °C was expected to be favourable to produce high phenol content in the bio-oil. Any temperature higher than this might cause negative effect on the phenol content.

3.5. Calorific value of the bio-char

The stirrer speed had a significant effect on the calorific value of the bio-char as shown in Fig. 6. Interestingly, the optimum value of calorific value for each stirrer speed was found at 50% MW absorber. It was observed that the calorific value was not only affected by MW absorber percentage (Salema and Ani, 2012b) but also with the stirrer speed. Highest calorific value of 29.5 MJ/kg was obtained at 50 rpm stirrer speed and 50% MW absorber percentage. At this condition, the temperature was in the range of 450–550 °C, which might favour complete destruction of biomass materials and increase the carbon and hydrogen contents in the bio-char. It was obvious from Fig. 6 that high stirrer speed lowered the calorific value of the bio-char. However, the exact reason for low CV at higher stirrer speed was not known. It was reported by Dominguez et al. (2007) that the energy content in the char decreases with increase in temperature. The calorific value of bio-char in present study was found to be higher than rice straw (19.6 MJ/kg) (Huang et al., 2008) and coffee hulls (24 MJ/kg) (Dominguez et al., 2007) pyrolysed under MW system. Not much investigation has been done on the calorific value of the MW pyrolysed char in the literature.

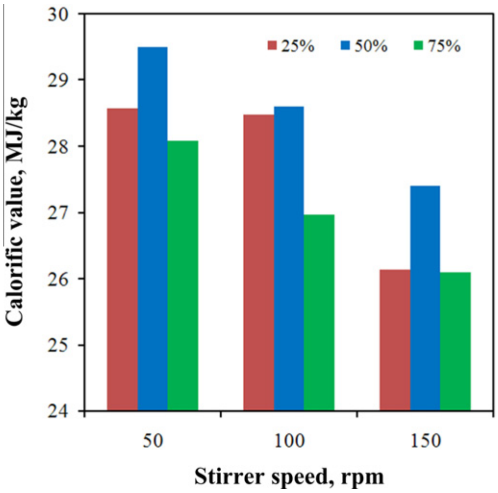

Fig. 6. Calorific value of bio-char obtained from MW pyrolysis of OPS.

4. Conclusions

The deposition of bio-oil in the reactor and equipment during MW pyrolysis was successfully eliminated by using simple technique. The results showed that the yield and chemical composition of bio-oil was significantly influenced by both stirrer speed and MW absorber percentage. Phenol was found to be major chemical fraction in the bio-oil which can be useful in phenolic applications as an alternative to petroleum-based phenols. The highest calorific value of 29.5 MJ/kg was obtained for bio-char which can serve as fuel in heating applications.

Acknowledgements

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